

**EFFECT OF LIQUID PROPERTIES (WATER AND LIME JUICE) ON
SPRAY CHARACTERISTICS OF DEFLECTED FLAT SPRAY NOZZLE
(AL-75)**

MUHAMMAD FAQHRURRAZI BIN ABD RAHMAN

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Mechanical Engineering

FACULTY OF MECHANICAL AND MANUFACTURING ENGINEERING

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

AUGUST 2017

SPECIAL GRATITUDE TO;

THE MOST BELOVED PARENTS,

Abd Rahman Bin Mohd Hasan and Fatimah Sham Binti Matt@Ahmad

For their support in whole of my life

MY HONOURED SUPERVISOR,

Assoc. Prof. Dr Norzelawati Binti Asmuin

For their advice, support and patience during completion this thesis

MY CO-SUPERVISOR

En. Mohamad Farid bin Sies

For their advice, support and patience during completion this thesis

SPECIAL THANK YOU FOR

All my friends

For their moral support, cooperation and assistance in this study

ACKNOWLEDGEMENT

Alhamdulillah praises to Allah S.W.T due to His will and gift and blessing upon Prophet Muhammad (p.b.u.h). By His grace, He places mankind on the friendly earth, provide them all with the necessities for healthy living, permits them the discovery of knowledge of science and application of technological skill for their physical advancement in this temporary life. Ultimately, all shall return to Allah, only the deed that pleases Him will remain on their credit for the internal life hereafter.

There are no proper word to convey my deep gratitude and respect for my supervisors, Assoc. Prof. Dr Norzelawati Binti Asmuin for guidance, encouragement and also the advice throughout my time as student him. Also for my co-supervisor Encik Mohammad Farid Bin Sies that always help me and assistance me until I finish my work. Only Allah S.W.T shall repay all him kindness. Special thanks to my parents Abd Rahman Bin Mohd Hasan and Fatimah Sham Binti Matt@Ahmad whom had always supported me and gave encouragement and motivation me during the course of this study.

My sincere thanks also goes to my friends who went through hard times together, gave advice and also constructive discussion sessions. Last but not least, I would like to thank those who have contributed directly or indirectly towards the success of this study.

ABSTRACT

Nowadays, the application of the nozzle has been widely used in the industry. The main factor that influences the spray is pressure of the liquid and air, type of nozzle, type of spray and the viscosity of the liquid. The problem in this research is to determine minimum liquid pressure used for atomization. This study is on characteristic with different ratio of liquid properties which can affect the spray behaviour for this spray such as spray angle, spray development and velocity. The objective for this research is to get the best atomizer within 1 bar to 3 bar liquid pressure for household piping. For this study, the pressure of liquid used was 1 bar, 2 bar and 3 bar, whereas the pressure of air used was 1 bar, 3 bar and 6 bar. Another objective is to identify characteristic study of spray angle, spray development and velocity of flat fan spray nozzle by using different liquid properties. 3 different fluids were tested with deflected flat spray nozzle (AL-75); 100% water, L10W90 (consist of 10% lime and 90% water) and L30W70 (consist of 30% lime and 70% water). Final objective is to validate result for spray angle and velocity between experiment and simulation using ANSYS CFX version 15.0. Based on the obtained results, the duration of fully development for deflected flat spray nozzle (AL-75) operated at the combination of 3 bar liquid pressure with 3 bar air pressure was 24ms, compared to spray nozzle operated at the combination of 1 bar liquid pressure with 1 bar air pressure with 32ms. This is because, an increase in pressure were decreases the duration for spray pattern to be fully developed. Velocity of 100% water was the highest compared to L10W90 and L30W70. This is due to the fact that as viscosity increased, the velocity of spray decreases. Spray angle result shows that water have wider angle compared to L10W90 and L30W70. As viscosity increased, the spray angles become narrow and simultaneously reduce the spray angle.

ABSTRAK

Pada masa kini, penggunaan muncung telah digunakan secara meluas dalam industri. Masalah kajian ini adalah untuk menentukan penggunaan tekanan rendah cecair untuk pengabusan. Kajian ini memberi tumpuan kepada ciri-ciri dengan nisbah cecair berbeza yang boleh mempengaruhi tingkah laku semburan seperti sudut semburan, perkembangan semburan dan halaju. Objektif kajian adalah mendapatkan pengabusan yang terbaik dalam tekanan 1 bar hingga 3 bar cecair untuk paip rumah. Untuk kajian ini, tekanan cecair yang digunakan adalah 1 bar, 2 bar dan 3 bar, manakala tekanan udara yang digunakan adalah 1 bar, 3 bar dan 6 bar. Objektif seterusnya adalah mengenal pasti ciri kajian sudut semburan, perkembangan semburan dan halaju muncung semburan rata dengan menggunakan cecair yang berbeza. 3 cecair yang berbeza telah diuji dengan muncung semburan kipas rata; 100% air, L10W90 (terdiri daripada 10% limau dan 90% air) dan L30W70 (terdiri daripada 30% limau dan 70% air). Objektif terakhir adalah untuk mengesahkan keputusan sudut semburan dan halaju daripada perbezaan eksperimen dan simulasi menggunakan ANSYS CFX versi 15.0. Berdasarkan keputusan, tempoh perkembangan sepenuhnya untuk muncung semburan rata (AL-75) pada kombinasi tekanan cecair 3 bar dengan tekanan udara 3 bar adalah 24ms, berbanding semburan muncung beroperasi pada gabungan 1 bar tekanan cecair dengan 1 bar tekanan udara 32ms. Ini kerana, peningkatan dalam tekanan mengurangkan tempoh untuk corak semburan. Halaju 100% air adalah yang tertinggi berbanding L10W90 dan L30W70. Ini disebabkan kelikatan meningkat, halaju semburan berkurangan. Sudut semburan menunjukkan bahawa air mempunyai sudut yang lebih luas berbanding L10W90 dan L30W70. Kelikatan meningkat, sudut semburan menjadi sempit dan pada masa yang sama mengurangkan sudut semburan.

CONTENT

TITLE	i
DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vi
TABLE OF CONTENT	vii
LIST OF FIGURES	xii
LIST OF TABLES	xvii
LIST OF SYMBOLS AND ABBREVIATIONS	xix
LIST OF APPENDICES	xx
LIST OF PUBLICATIONS	xxi
CHAPTER 1 INTRODUCTION	1
1.1 Background study	1
1.2 Problem statement	2
1.3 Objectives	3
1.4 Scope of study	3
1.5 Outline of the thesis	4

CHAPTER 2 LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Atomization	5
2.2.1 Droplet size	6
2.3 Spray nozzle	7
2.3.1 Two fluid nozzle	9
2.3.1.1 Internal mixing nozzle	9
2.3.1.2 Flow principle for spray nozzle	10
2.4 Types of spray nozzle	12
2.4.1 Standard flat fan spray nozzle	12
2.4.2 Full cone spray nozzle	13
2.4.3 Hollow cone spray nozzle	13
2.4.4 Deflected flat spray nozzle	14
2.5 Spray nozzle performance	15
2.5.1 Spray angle affected by viscosity and pressure	16
2.5.2 Velocity affected by viscosity and pressure	20
2.6 Image capture	22
2.6.1 High speed camera	23
2.6.2 Tracker software	25
2.6.3 ImageJ	27
2.7 Computational fluid dynamics (CFD)	30
2.7.1 Turbulence modelling	31
2.8 Lime juice	32
2.9 Flow rate	32
2.10 Summary	33

CHAPTER 3 METHODOLOGY	34
3.1 Introduction	34
3.2 Flow chart experimental and simulation on deflected flat spray nozzle	35
3.3 Spray nozzle	37
3.3.1 Deflected flat spray nozzle	38
3.4 Lime and water as liquid for deflected flat spray nozzle	39
3.4.1 Density and viscosity for the lime	39
3.4.2 Liquid and air pressure for deflected flat spray nozzle	41
3.4.3 Flow rate for water, L10W90 and L30W70	41
3.5 Experimental setup procedure	45
3.5.1 Apparatus and equipment	47
3.6 Phantom camera control software (PCC)	53
3.7 Velocity trace by tracker software	56
3.8 Spray angle trace by imageJ	59
3.9 Calculation of molar mass and density of citric acid and water	61
3.10 Choosing simulation on deflected flat spray nozzle	63
3.10.1 Geometry for deflected flat spray nozzle	64
3.10.2 Meshing for deflected flat spray nozzle	65
3.10.3 Mesh quality: skewness and orthogonal	66
3.10.4 Parameter setup for ANSYS CFX	67
CHAPTER 4 RESULTS AND DISCUSSIONS	68
4.1 Introduction	68
4.2 Spray development for deflected flat spray nozzle	68
4.2.1 Spray development for 1 bar liquid 1 bar air	69

4.2.2	Spray development for 2 bar liquid 1 bar air	70
4.2.3	Spray development for 2 bar liquid 3 bar air	71
4.2.4	Spray development for 3 bar liquid 1 bar air	72
4.2.5	Spray development for 3 bar liquid 3 bar air	73
4.2.6	Spray development for 3 bar liquid 6 bar air	74
4.2.7	Tulip and distorted pencil condition	75
4.3	Calculation of boundary condition in simulation	77
4.3.1	Setup for deflected flat spray nozzle	79
4.4	Calculation of velocity for simulation and experiment	83
4.5	Validation on the simulation	86
4.5.1	3 bar liquid 3 bar air using water as the working fluid	87
4.5.2	3 bar liquid 3 bar air using L10W90 as the working fluid	89
4.5.3	3 bar liquid 3 bar air using L30W70 as the working fluid	91
4.6	Validation of the simulation using experimental data	93
4.6.1	Spray angle for 3 bar liquid 3 bar air using water as the working fluid	93
4.6.2	Spray angle for 3 bar liquid 3 bar air using L10W90 as the working fluid	95
4.6.3	Spray angle for 3 bar liquid 3 bar air using L30W70 as the working fluid	96
4.7	Discussions	98
4.7.1	Effects on velocity by varying operating pressure (experiment)	98
4.7.2	Effects on spray angle by varying operating pressure (experiment)	99

4.7.3	Effect on velocity by varying operating pressure (simulation and experiment)	100
4.7.4	Effect on spray angle by varying operating pressure (simulation and experiment)	101
CHAPTER 5 CONCLUSION AND RECOMMENDATION		102
5.1	Conclusion	102
5.2	Recommendation	103
REFERENCES		104
APPENDICES		108



LIST OF FIGURES

Figure 2.1	Atomization phases	6
Figure 2.2	Categories of droplet size in micron	7
Figure 2.3	Properties of sprays and examples of their uses	8
Figure 2.4	Spray nozzle	9
Figure 2.5	Internal mixing nozzle	10
Figure 2.6	Flow principle of the spray nozzle	11
Figure 2.7	Standard flat-fan nozzle	12
Figure 2.8	Full cone spray nozzle	13
Figure 2.9	Hollow cone nozzle	14
Figure 2.10	Deflected flat spray nozzle	15
Figure 2.11	Fluid viscosity against cone angle	18
Figure 2.12	Schematic of experimental Rig for Cold Flow Test	19
Figure 2.13	Effect of injection pressure and the number of inlet slot on spray cone angle	20
Figure 2.14	Velocity against viscosity bar chart	21
Figure 2.15	Geometry model of the jet flow field	21
Figure 2.16	Effect of nozzle pressure drop on nozzle outlet velocity	22
Figure 2.17	The experimental section in operation, reacting flow condition	23
Figure 2.18	Bubble emerging from flush-mounted nozzle	24
Figure 2.19	Experimental setup for visual observation of electrospray	24
Figure 2.20	Camera snapshot of the electrospray of the pure water	25
Figure 2.21	Analysis using the tracker program	26

Figure 2.22	Analysis of time dependence for the position (square) and velocity (circle) of a metal ball, exploring the mathematical operations of integrations and derivation	27
Figure 2.23	Schematic diagram of newly designed atomizer	28
Figure 2.24	Binary conversion	29
Figure 2.25	Angle measurements using the angle tools in imageJ	29
Figure 2.26	Streamline of velocity distribution in a nozzle geometry	31
Figure 2.27	The effects of pressure on nozzle mass flow rates	33
Figure 3.1	Flow chart for experimental and simulation	35
Figure 3.2	Deflected flat spray nozzle (AL-75) from Delavan spray	37
Figure 3.3	Dimension for the AL-75 nozzle	38
Figure 3.4	Deflected Flat spray nozzle	38
Figure 3.5	Experimental setup	45
Figure 3.6	Schematic diagram of the experimental setup	45
Figure 3.7	High Speed Camera	48
Figure 3.8	Air compressor	49
Figure 3.9	Water pressure tank	49
Figure 3.10	Air flow meter	49
Figure 3.11	Water flow meter	50
Figure 3.12	Nikon DSLR D7000 Camera	51
Figure 3.13	50 mm F2 Carl Zeiss lens	51
Figure 3.14	Spotlight Arrilite 1000	52
Figure 3.15	Spotlight stand	52
Figure 3.16	Pressure gauge	52
Figure 3.17	An example of PCC image of AL-75 spray nozzle	53
Figure 3.18	Fully developed spray captured by using Phantom Camera Control (PCC) for 1 bar liquid 1 bar air with water as the working fluid	54
Figure 3.19	Fully developed spray captured by using Phantom Camera Control (PCC) for 3 bar liquid 3 bar air using water as the working fluid	55

Figure 3.20	Image of fully developed spray for 3 bar liquid 3 bar air in Tracker software	56
Figure 3.21	Graph and table for 3 bar liquid 3 bar air using water as working fluid in Tracker software	57
Figure 3.22	ImageJ software	59
Figure 3.23	The image from Nikon DSLR D7000 camera Transferred into imageJ	59
Figure 3.24	The spray image after being invert	60
Figure 3.25	Image of spray angle after measurement	60
Figure 3.26	ANSYS Software	63
Figure 3.27	Geometry of deflected flat spray nozzle (AL-75)	64
Figure 3.28	Meshing of deflected flat spray nozzle (AL-75)	65
Figure 3.29	Skewness value and orthogonal value	66
Figure 4.1	Stage of spray development for water, L10W90 and L30W70 for (8000 fps) for 1 bar liquid 1 bar air pressure	69
Figure 4.2	Stage of spray development for water, L10W90 and L30W70 for (8000 fps) for 2 bar liquid 1 bar air pressure	70
Figure 4.3	Stage of spray development for water, L10W90 and L30W70 for (10000 fps) for 2 bar liquid 3 bar air pressure	71
Figure 4.4	Stage of spray development for 3 bar liquid 1 bar air using water, L10W90 and L30W70 as working fluid at 8000 fps	72
Figure 4.5	Stage of spray development for 3 bar liquid 3 bar air using water, L10W90 and L30W70 as working fluid at 10000 fps	73
Figure 4.6	Stage of spray development for 3 bar liquid 6 bar air using water, L10W90 and L30W70 as working fluid at 10000 fps	74
Figure 4.7	Tulip condition in (a) 1 bar liquid 1 bar air, (b) 2 bar liquid 1 bar air, (c) 2 bar liquid 3 bar air and (d) 3 bar liquid 1 bar air	75

Figure 4.8	Distorted pencil condition for deflected flat spray nozzle for 3 bar liquid 1 bar air	76
Figure 4.9	Tulip condition for deflected flat spray nozzle for 3 bar liquid 1 bar air	77
Figure 4.10	Geometry of AL-75 spray nozzle for this simulation	80
Figure 4.11	Air inlet for AL-75 spray nozzle	81
Figure 4.12	Water/Lime inlet for AL-75 spray nozzle	82
Figure 4.13	Water velocity contour for 3 bar liquid 3 bar air using water as working fluid	82
Figure 4.14	Trigonometry method used in the tracker for the experiment	83
Figure 4.15	The position of probe for zero gradients	85
Figure 4.16	The point for the final velocity	86
Figure 4.17	Experiment result for 3 bar liquid 3 bar air using water as the working fluid	87
Figure 4.18	Simulation result for 3 bar liquid 3 bar air using water as the working fluid	88
Figure 4.19	Experimental result for 3 bar liquid 3 bar air using L10W90 as the working fluid	89
Figure 4.20	Simulation result for 3 bar liquid 3 bar air using L10W90 as the working fluid	90
Figure 4.21	Experimental result for 3 bar liquid 3 bar air using L30W70 as the working fluid	91
Figure 4.22	Simulation result for 3 bar liquid 3 bar air using L30W70 as the working fluid	92
Figure 4.23	The spray angle from the experiment for 3 bar liquid 3 bar air using water as the working fluid	94
Figure 4.24	The spray angle from the simulation for 3 bar liquid 3 bar air using water as the working fluid	94
Figure 4.25	The spray angle from the experiment result for 3 bar liquid 3 bar air using L10W90 as the working fluid	95
Figure 4.26	The spray angle from the simulation result for 3 bar liquid 3 bar air using L10W90 as the working fluid	96

Figure 4.27	The spray angle from the experiment result for 3 bar liquid 3 bar air using L30W70 as the working fluid	97
Figure 4.28	The spray angle from the simulation result for 3 bar liquid 3 bar air using L30W70 as the working fluid	97



LIST OF TABLES

Table 2.1	Summaries for the various factors that affect the spray performance	15
Table 2.2	Suggested minimum spray heights	16
Table 2.3	Viscosities of water glycerol mixture fluids at 23.3°C	17
Table 2.4	Volume ratio of glycerol with cone angle	17
Table 2.5	Viscosity of mixture distilled water with different percentage of Glycerine	20
Table 3.1	Properties of lime and water mixing used in the simulation obtained by experiment	39
Table 3.2	Density of lime juice + raw water	39
Table 3.3	Viscosity rate for lime juice + distilled water	40
Table 3.4	Pressure of both liquid and air for 6 different cases	41
Table 3.5	Flow rate for water	43
Table 3.6	Flow rate for L10W90	43
Table 3.7	Flow rate for L30W70	44
Table 3.8	Specification for Phantom Camera Control V710	47
Table 3.9	Specification for Nikon DSLR D7000	50
Table 3.10	Average velocity value for 3 bar liquid 3 bar air using water as working fluid using Microsoft Excel	57
Table 3.11	Element of Citric Acid properties	61
Table 3.12	Element of Water properties	61
Table 3.13	Meshing properties in ANSYS CFX for Flat spray nozzle (AL-75)	65
Table 3.14	Skewness and Orthogonal for flat spray nozzle (AL-75)	66
Table 3.15	Parameter setup for deflected flat spray nozzle	67

Table 4.1	Flow rate for Water, L10W90 and L30W70 in pressure 3 bar liquid 3 bar air	77
Table 4.2	The velocity calculated for all working fluid	79
Table 4.3	Reynolds number for Deflected flat spray nozzle (AL-75)	80
Table 4.4	Material properties in ANSYS CFX Simulation	81
Table 4.5	The average velocity value for 3 bar liquid 3 bar air using water as the working fluid	88
Table 4.6	The average velocity value for 3 bar liquid 3 bars air using L10W90 as the working fluid	90
Table 4.7	The average velocity value for 3 bar liquid 3 bars air using L30W70 as the working fluid	92
Table 4.8	Experiment velocity for 3 bar liquid 3 bar air and 3 bar liquid 6 bar air	98
Table 4.9	Experiment spray angle for 3 bar liquid 3 bar air and 3 bar liquid 6 bar air	99
Table 4.10	Comparison velocity between experiment and simulation for 3 bar liquid 3 bar air	100
Table 4.11	Comparison spray angle between experiment and simulation for 3 bar liquid 3 bar air	101



LIST OF SYMBOLS AND ABBREVIATIONS

CFD	-	Computational Flow Dynamics
3D	-	3 Dimensional
ρ	-	Density
D	-	Diameter
μ	-	Dynamic Viscosity
v	-	Velocity
VOC	-	Volatile Organic Compounds
KH ₂ PO ₄	-	Monopotassium Phosphate
COD	-	Chemical Oxygen Demand
RO	-	Reverse Osmosis
La(NO ₃) ₃ ·6H ₂ O	-	Lanthanum (II) Nitrate Hexahydrate
Mn (NO ₃) ₂ ·4H ₂ O	-	Manganese (II) Nitrate Tetrahydrate
Co(NO ₃) ₂ ·6H ₂ O	-	Cobaltous Nitrate Hexahydrate
LaMnO ₃	-	Lanthanum Manganate
LaCoO ₃	-	Lanthanum Silicate Oxypatite
H	-	Hydrogen
O	-	Oxygen

LIST OF APPENDICES

Publications

107



LIST OF PUBLICATIONS

1. Analysis mist spray development with Al-75 nozzle by using high speed camera. AIP Conference Proceedings 1831, 020023 (2017); doi: <http://dx.doi.org/10.1063/1.4981164>



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 1

INTRODUCTION

1.1 Background study

In the 20th century, the demand of mist spray nozzle is very high in various companies especially which involve with cleaning process. Multiphase flow is described as any fluid consisting of more than one phase or component. There are two types of nozzle that had been widely used in the industry, namely deflected flat spray nozzle and jet nozzle. The jet nozzle performs quite well compared to flat spray nozzle. However, it uses more water. Most industry wanted to reduce the usage of water to cut the cost incurred during production. As for deflected flat spray nozzle, only a small amount of water mixed with lime was used. The main objective of using the deflected flat spray nozzle in kitchen hood is to clean the grease and at the same time act as surface cooler.

In spraying system, nozzles break the liquid into the droplets. Droplet size refers to the size of the individual drops that comprise a nozzle spray pattern. There are many factors that affecting the fluid properties of the spray such as surface tension, viscosity and density (Graco, 1995). For the surface tension, it is important to stabilize a fluid and the higher the surface tension can produce the larger average droplet size upon the atomization. The viscosity can cause the fluid to resist agitation and tending to prevent its breakup. The increase viscosity produces the slower velocity for the spray nozzle and the larger droplets were produce. For the spray angle, the higher the viscosity, the narrow the spray angle was produced. The density

can cause the fluid to resist acceleration. Higher density tends to result in a larger average droplet size (Nuyttensa et al., 2007)

The nozzle used for this study is deflected flat spray nozzle (AL-75). This nozzle was used because the lower pressure for air and water can be applied into it. These nozzles are used to clean up the filter by using water; however, the cleanliness quality of the filter is not satisfactory because water is not good cleaning agent to clean the oil and grease in the filter. Therefore, the organic citric acid mix with water was suggested for another alternative as a cleaning agent. Organic citric acid is good agents to kill bacteria, mold and mildew for great general disinfecting and safety cleaning agent. The operation pressure used for this experiment is 1 bar, 2 bar and 3 bar for liquid pressure and 1 bar, 3 bar and 6 bar for air pressure.

The software that was used in this research was ANSYS software. ANSYS software is widely used in variety of industry involving engineering projects because it can design the process. For this research, the ANSYS software can predict the simulation in the nozzle. The simulations using ANSYS software provide prediction on flow behaviour of the nozzle.

1.2 Problem statement

Nowadays the spray nozzle is often used for industry such as spraying in painting, filtering and cleaning. Most of pressure use to atomize the liquid are above 6 bar for example jet nozzle atomized above 150 bar (Tamaki & Shimizu, 2002) while macro spray nozzle and single point nozzle atomized at 34 bar (Hannifin, 2013) and pressure swirl nozzle atomized at 6 bar liquid pressure (Schuchmann & Gaukel, 2015). The problem in this research is to determine minimum liquid pressure used for best atomization in household piping system. According to this research also focus on characteristic study with different ratio of liquid properties which can affect the spray behaviour such as spray angle, spray development and velocity.

1.3 Objectives

The objectives of this study are:

- i. To obtain the best atomizer configuration within 1 bar to 3 bar liquid pressure for household piping and 1 bar, 3 bar and 6 bar for air pressure.
- ii. To identify characteristic study by using different liquid properties.
- iii. To validate the Computational Fluid Dynamic (CFD) result using ANSYS CFX with experimental for spray angle and velocity.

1.4 Scope of study

The scope of study is limited to:

- i. Liquid pressure used in experiment are 1 bar, 2 bar and 3 bar, and air pressure from 1 bar, 3 bar and 6 bar.
- ii. Percentage ratio of water and limes as liquids
 - a) 10% lime juice and 90% water (L10W90)
 - b) 30% lime juice and 70% water (L30W70)
 - c) 100% of water (L0W100)
- iii. Deflected flat spray nozzle (AL-75) was used in the experiment.
- iv. High speed camera (Phantom V710) used for detected spray development with the following specifications; maximum resolution of 1280x800 at 7500 fps, minimum resolution of 128x8 at 1400000 fps (optional) and 685800 fps (standard). Image sensor of MOS sensor having 20 μm pixel size. Phantom Camera Control (PCC) with speed of 7.5 Gpx/Sec and recording time of 2.97s at maximum frame rate.
- v. Nikon D7000 Camera used to capture the spray angle with 16.9 million effective pixels and the speed of 1/8000. The flash sync or frame rate of this camera is 1/250 per seconds. CMOS Image sensor of 23.6x15.6 mm.

- vi. Software used in experiment:
 - a) ImageJ
 - b) Tracker
 - c) Phantom Camera Control
 - d) Adobe Photoshop CS5 Extended
- vii. Software used in simulation:
 - a) Computational Fluid Dynamics (CFD) ANSYS CFX version 15.0 for simulation
 - b) Turbulence model used for simulation is K-epsilon

1.5 Outline of the thesis

This outline provides a summary of the contents of each chapter in this research and it is given as below:

CHAPTER 1 has introduced the alternative used for the spray nozzle, the pressure and liquid properties were used for this study.

CHAPTER 2 explains the necessary background for the deflected flat spray nozzle, the theory for spray nozzle and tools that were used for this experiment and simulation that are involved in this thesis.

CHAPTER 3 discussed the procedures for the experimental and simulation set up as well, including experimental tools and parameter setup for ANSYS software.

CHAPTER 4 present all the experiment result and the validation simulation result by ANSYS software. Discussed the result get from the experiment and simulation.

CHAPTER 5 conclude the result from entire thesis and suggest the recommendation for the future studies.

REFERENCES

- Andersson, A. G., Andreasson, P., & Staffan, T. (2010). Simulation of free surface flow in a spillway with the rigid lid and volume of fluid methods and validation in a scale model. *V European Conference on Computational Fluid Dynamics (ECCOMAS)*, 14-17.
- Bete.F.N (2013). *Handbook of nozzles for industry, pollution control, and fire protection*. Greenfield, United States. Engineered Spray Solution.
- Carrión, M.Steijl, R.,Woodgate, M.,Barakos, G.N., Munduate & Gomez-Iradi,S (2014). Aeroelastic analysis of wind turbines using a tightly coupled CFD–CSD method. *Journal of Fluids and Structures*, 50, 392–415.
- Chengzheng Cai, G. li, Z. Huang, F. G (2017). Velocity Distribution Characteristics and Parametric Sensitivity Analysis of Liquid Nitrogen Jet. *Journal of GeoMechanics and Deep Underground Engineering*, 37(1), 1-10.
- District, M., & Kaen, K. (2008). Continuous Production of Lime Juice by Vacuum. *American Journal of Applied Sciences*, 5(8), 959-962.
- Ghaffar, Z. A., Kasolang, S., Hussein, A., Hamid, A., Sheng, O. C., Azlina, M., & Bakar, A. (2015). Effect of geometrical parameters interaction on swirl effervescent atomizer spray angle. *Jurnal Teknologi (Science & Engimeering)*, 76(9), 63-67.
- Gottlieb,N.,Schwartzbach, C.,& Denmark, N.A.S. (2004). Development of an internal mixing two-fluid nozzle by systematic variation of internal parts. *Journal of Fluids and Structures*, 1-7.
- Hannifin.P (2013). *Handbook of Redefining Spray Technology*Macro spray nozzle technology. America, U.S.A. Gas Turbine Fuel Systems Division.

- Hussein.A, M.Hafiz, H.Rashid, A.Halim, W.Wisnoe, S.Kasolang (2012). Characteristics of Hollow Cone Swirl Spray at Various Nozzle Orifice Diameters. *Jurnal Teknologi (Science & Engineering)*, 58(2), 1- 4.
- Hockicko, P (2012). Attractiveness of Learning Physics by Means of Video Analysis and Modeling Tools. *Journal of Physics and Engineering*. 40, 1-8.
- Hockicko, P. (2011). Forming of physical knowledge in engineering education with the aim to make physics more attractive. *Journal of Physics and Engineering*, 34, 1-5.
- Keuchi, H (2013). *Handbook of pneumatic spray nozzles*. Japan, Osaka. The Mist Engineers.
- Kim, H., Kim, J., & Ogata, A. (2011). Time-resolved high-speed camera observation of electrospray. *Journal of Aerosol Science*, 42(4), 249–263.
- Linck, M. B., Gupta, A. K., Bourhis, G., & Yu, K. (2013). Flame and Unsteady Two-Phase Exhaust Jet. *Journal of America Institute Aeronautics and Astronautics*, 1-15.
- López-cruz, I. L., & Rojano-aguilar, A. (2010). Advances in Computational Fluid Dynamics Applied to the Greenhouse Environment. *Journal of Agricultural Engineering*, 40(2), 1-15.
- Lukas Durdina, Jan Jedelsky, Miroslav Jicha (2014). Investigation and comparison of spray characteristics of pressure-swirl atomizers for a small-sized aircraft turbine engine. *International Journal of Heat and Mass Transfer*, 66, 892-900.
- Mansour, N. N., Kim, J., & Moinj, P. (2013). Near-Wall k-ε Turbulence Modeling. *Journal of America Institute of Aeronautics and Astronautics*, 27(8),1068-1073.
- Graco .I (1995). *Handbook of Atomization Concept and Theory*. Minneapolis, U.S.A. Airless Spray Techniques Concept and Theory.
- Monte P. Johnson, Entomology, and L. D. S. (2014). Spray Performance Considerations Technical Reference Spray Performance Considerations. *Journal of Fluids and Structures*, 2-3.
- Murakami, T., Hodgins, G., & Simon, A. W. (2013). Characterization of lime carbonates in plasters from Teotihuacan, Mexico: preliminary results of cathodoluminescence and carbon isotope analyses. *Journal of Archaeological Science*, 40(2), 960-970.

- Nogami, N., Hirabayashi, A., White, J., & Condat, L. (2015). Improvement of pixel enhancement algorithm for high-speed camera imaging using 3D sparsity. *Journal of Science and Engineering*, 68(7), 952-957.
- Nuytensa. D, K.Baetensb, M.De Schamphelerec, B.Soncka (2007). Effect of nozzle type, size and pressure on spray droplet characteristics. *Journal of Biosystems Engineering*, 97(20), 333-345.
- Petersen, D. (2013). *Handbook of ASAE S-572 Spray Tip Classification by Droplet Size*. Oregon State University, United States: Spray Tips, Droplet size & Calibration.
- Raman, I., Syafiq, M., Sa, N., Ibrahim, M., & Wahab, M. S. (2013). Viscosity effect on Piezoelectric Actuated Nozzle In Generating Micro Droplet. *Journal of Technology and Materials Engineering*, 626, 415-419.
- Robert Grisso, Pat hipkins, S. D. askew. (2013). Nozzles : Selection and Sizing. *Journal of Agriculture and Life Sciences*, 442(32), 1-15.
- Rudolf J. Schick (2006). *Handbook of Spray Technology Reference Guide: Understanding Drop Size*. Wheaton. U.S.A: Spray analysis and research services.
- Sayinci, B. (2015). Effect of strainer type, spray pressure, and orifice size on the discharge coefficient of standard flat-fan nozzles. *Turkish Journal of Agriculture and Forestry*, 39, 692-704.
- Schindelin, J., Rueden, C. T., Hiner, M. C., & Eliceiri, K. W. (2015). The imageJ ecosystem: An open platform for biomedical image analysis. *Molecular Reproduction and Development*, 82(7-8), 518–29.
- Schuchmann, H. P., & Gaukel, V. (2015). Performance and efficiency of pressure-swirl and twin-fluid nozzles spraying food liquids with varying viscosity. *Journal of Food Process Engineering ISSN*, 1745–4530, 1-12.
- Sharma,A. ,Kothari,A., Agrawal,A., Gandhi,R., Vishwavidyalaya, P.,Gandhi, R.,Vishwavidyalaya, P. (2013). Numerical simulation and CFD analysis for energy loss computation in fully open geometry of pelton turbine nozzle. *Journal of Latest Research in Science and Technology*, 2(1), 586-593.
- Sies, M. F, Asmuin, N., F., N.a., N., Zakaria, H., Pairan, R., & Sadikin, A. (2016). Determine Physical Properties of an Organic Citric Acid (Processed Lime Juice) Dissolve With Water Using Experimental Apparatus. *International Journal of Engineering and Technology*, 8(6), 2530–2536.

- Syazwan, M., Mat, F., Hussein, A., Hamid, A., Sheng, O. C., & Ghaffar, A. (2012). Effect of Inlet Slot Number on the Spray Cone Angle and Discharge Coefficient of Swirl Atomizer. *Journal of Procedia Engineering*, 41(IRIS), 1781-1786.
- Tamaki, N., & Shimizu, M. (2002). Enhancement of atomization of high-viscous liquid jet by pressure atomized nozzle. *Journal of Fluids and Structures*, 9(11), 1-7.
- Varun.K R, Rajashekhar. C. R, Bhaskar Dixit (2013). Spray characterization of nozzle for fire extinguisher. *International Journal of Modern Engineering Research (IJMER)*, 3(2), 793-797.
- Xie J.L., Z.W. Gan, F. Duan, T.N. Wong, S.C.M. Yu, R. Zhao (2013). Characterization of spray atomization and heat transfer of pressure swirl nozzles. *International Journal of Thermal Sciences*, 68, 94-102.
- Yao, S., Zhang, J., & Fang, T. (2012). Effect of viscosities on structure and instability of sprays from a swirl atomizer. *Experimental Thermal and Fluid Science*, 39, 158–166.
- Yao, Tanaka, S. & K. (2015). Design Procedure and Performance Evaluation of a Flat-Jet Twin-Fluid Atomizer by Siphoning Liquid. *International Journal of Engineering and Technology*, 7(5), 1-7.
- Yule, A. J. (2015). *Handbook of Introduction to industrial spray*. Springer-Verlag. London: Industrial Sprays and Atomization.
- Zhou, W., Hu, J., Feng, M., Yang, B., & Cai, X. (2015). Particuology Study on imaging method for measuring droplet size in large spray. *Journal of Science and Technology*, 22, 100- 106.